Building Foundation Models for BCIs:

Fundamentals & Opportunities

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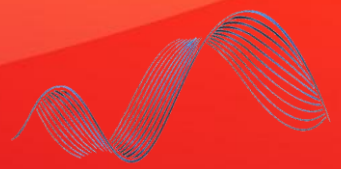


WAVES LAB

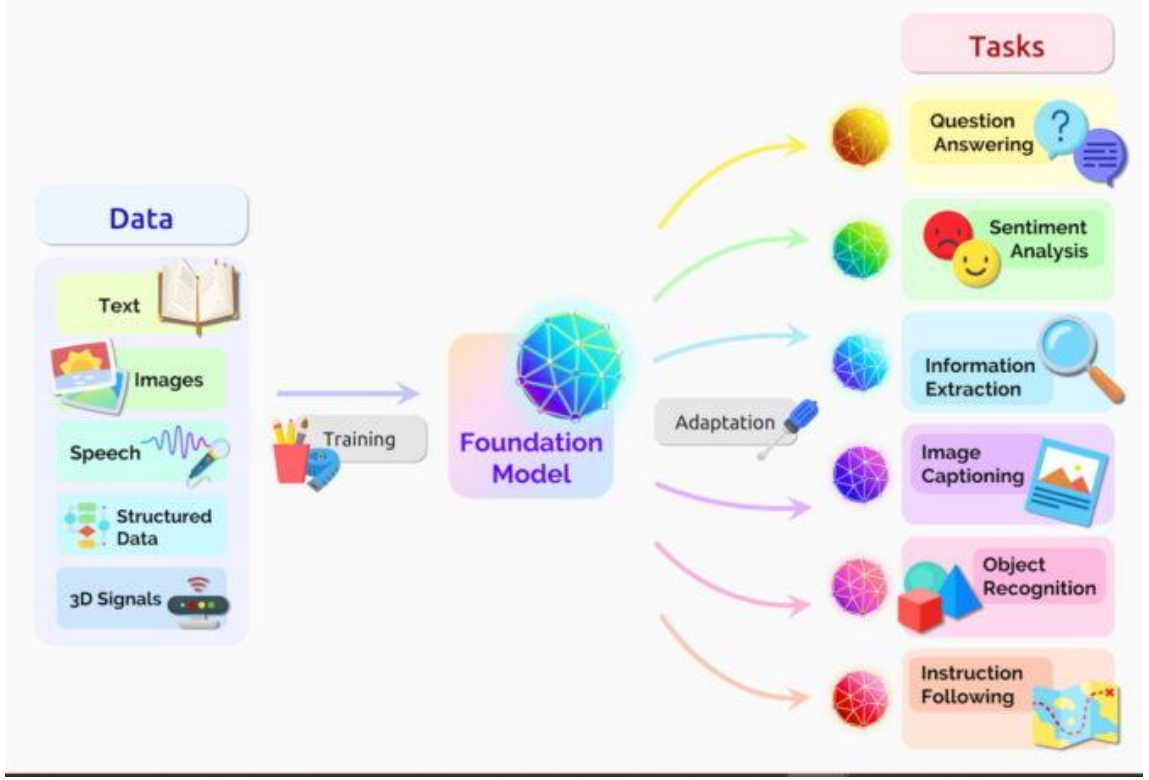
BCI SOCIETY

W7: Bridging AI Expertise with BCI Champions to Advance AI Innovation in BCIs, June 2025

UNIVERSITY OF CALGARY

Foundation Models (FM) – A paradigm shift in AI

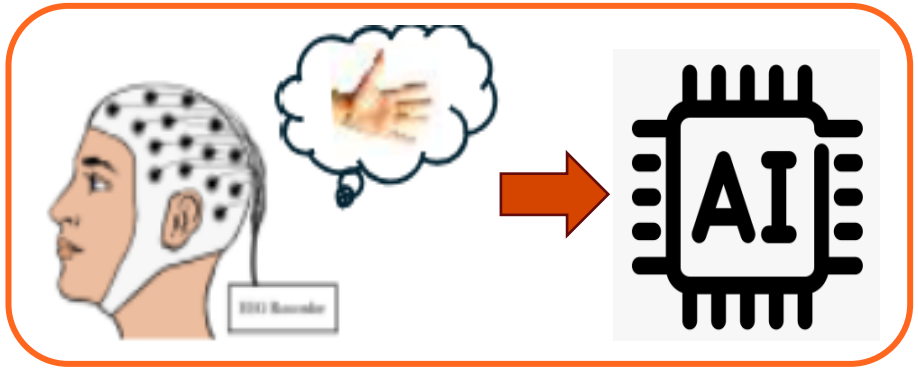
- Foundation models are (usually) large, *pre-trained AI models* that enable a wide range of tasks without needing lots of labeled data.
- ChatGPT is built on a foundation model



https://blogs.nvidia.com/blog/what-are-foundation-models/

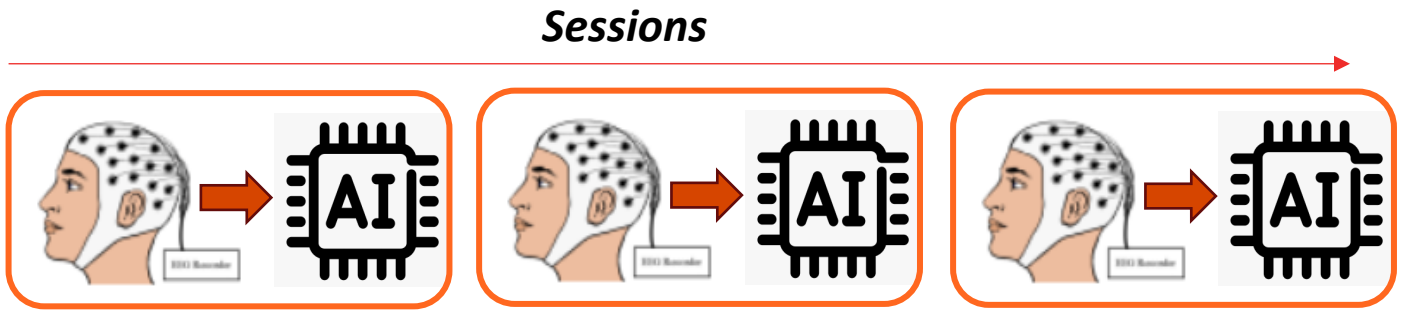
Supervised Learning (Traditional)

1. Collect data and LABEL it (e.g. left & right motions)
2. Build an AI model for this data



AI Generalization Challenges in BCIs

1. Models do NOT generalize to different BCI *sessions*



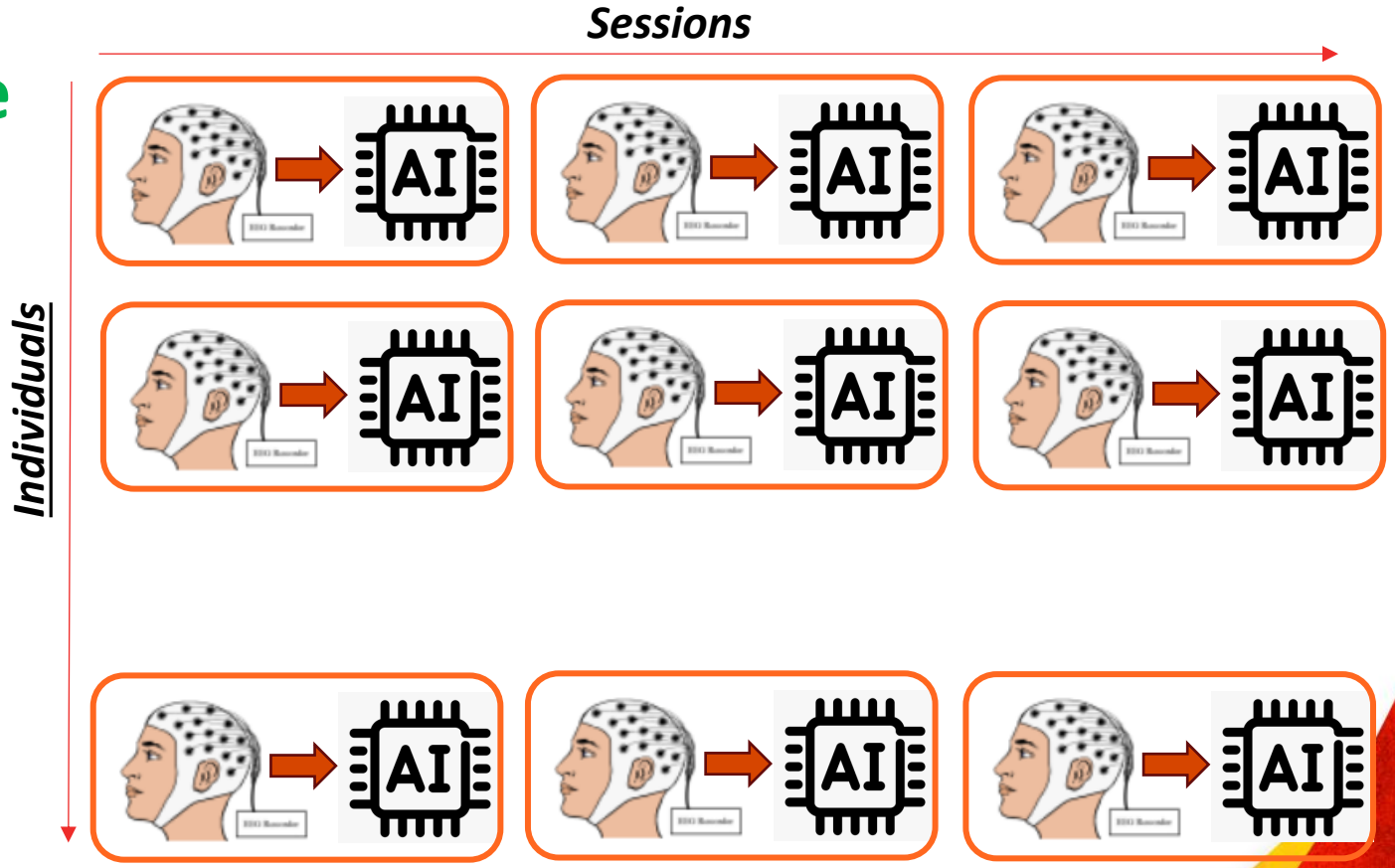
Considerable “calibration time”

Calibration is tiring.

AI Generalization Challenges in BCIs

2. Models do not generalize to different *individuals*

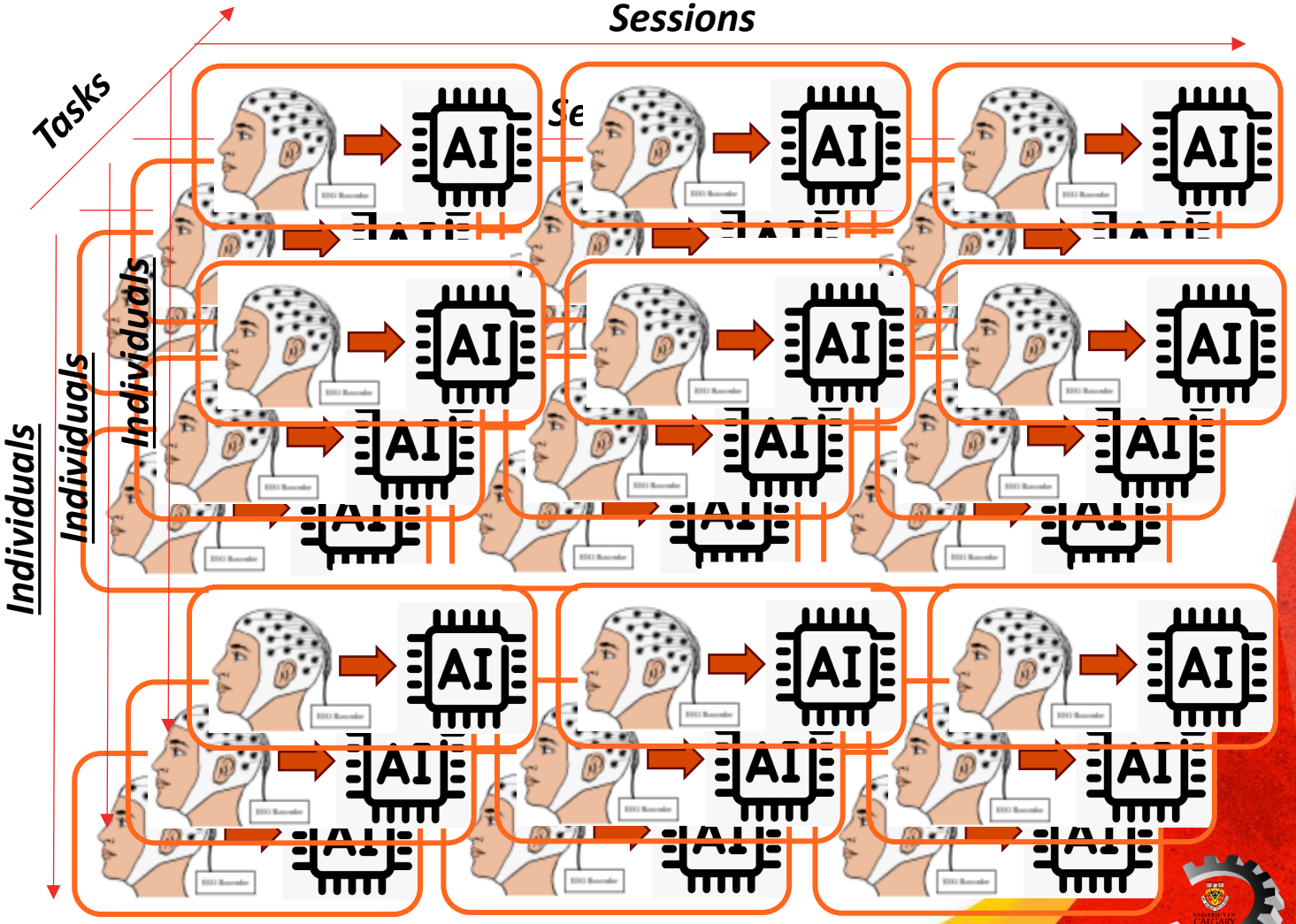
A model per individual is needed!



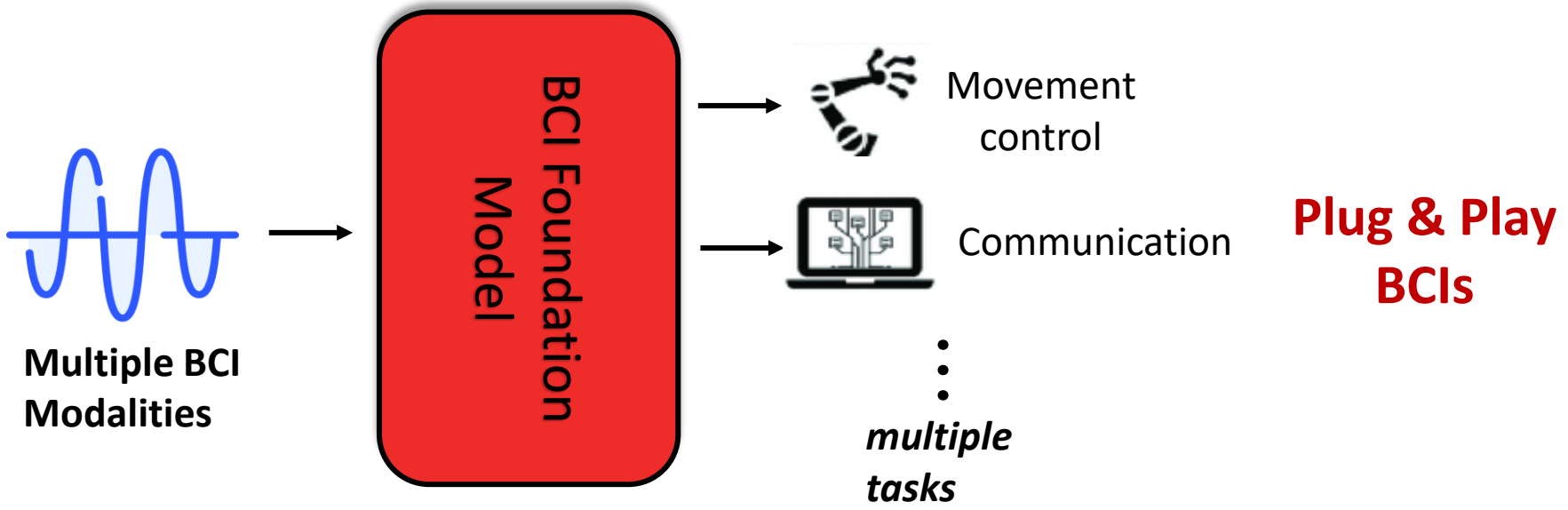
AI Generalization Challenges in BCIs

3. Models do not generalize to *different tasks and modalities*

A model *per task per individual* that is calibrated *per session*!

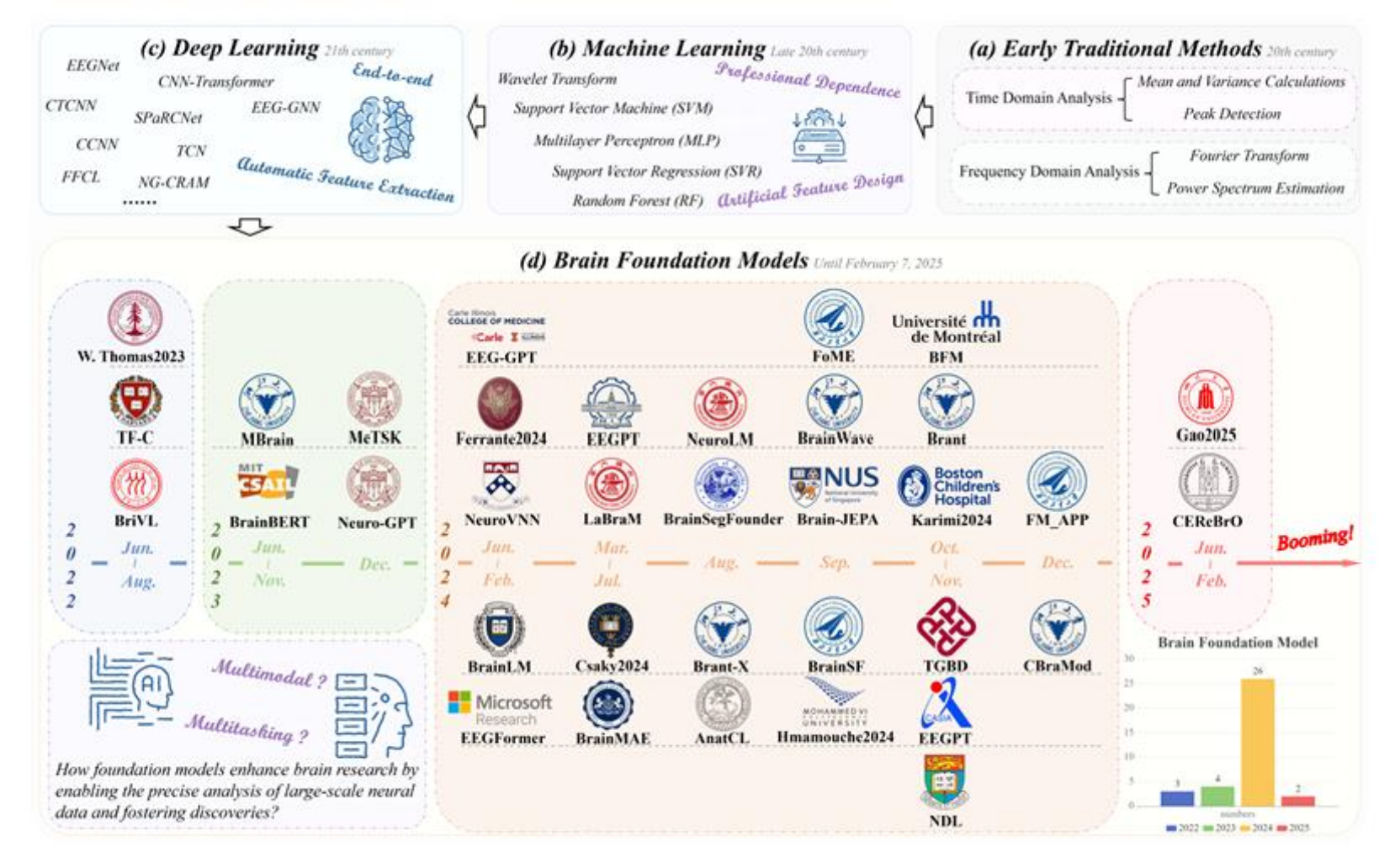


(Why) Build BCI Foundation Models



- **Generalization**: The model has learned from a **diverse range of data**, so it performs well on **unseen scenarios and new tasks**
- **Data Efficiency**: Traditional models need lots of labeled data, **foundation models perform well with small datasets**.
- **Scalability**: Instead of training a new model for each task, **one powerful model** can handle multiple tasks.

BCI Foundation Models are happening!



Zhou, Xinliang, et al. "Brain Foundation Models: A Survey on Advancements in Neural Signal Processing and Brain Discovery." *arXiv preprint arXiv:2503.00580* (2025).

BCI Foundation Models are happening!

TABLE II

SUMMARY OF TYPICAL BFMS FOR BRAIN DECODING.

Model	Pretraining	Fine-tuning	Cross Scenarios	Cross Tasks	Multi Modalities
BrainLM [19]	✓	×	✓	✓	×
LaBraM [25]	✓	✓	✓	✓	×
NeuroLM [20]	✓	×	✓	✓	✓
Brant [14]	✓	✓	✓	✓	×
BrainSegFounder [26]	✓	✓	×	×	✓
MeTSK [27]	✓	✓	×	✓	×
AnatCL [28]	✓	×	✓	✓	×
BRAINBERT [29]	✓	✓	✓	✓	×
NeuroVNN [29]	✓	✓	✓	×	×
Brain-JEPA [13]	✓	✓	×	✓	×
FoME [30]	✓	✓	✓	✓	×
FM-BIM [31]	✓	✓	×	✓	×
BrainWave [32]	✓	✓	✓	✓	✓
TF-C [33]	✓	✓	×	✓	✓
Neuro-GPT [34]	✓	✓	✓	×	×
BrainMAE [35]	✓	✓	✓	✓	×
EEGFormer [36]	✓	✓	×	✓	×
CEReBrO [37]	✓	✓	×	✓	×
CBraMod [16]	✓	✓	✓	✓	×
EEGPT-Yue [38]	✓	✓	✓	✓	×
TGBD [23]	✓	×	✓	×	×
MBrain [21]	✓	✓	✓	×	✓
EEGPT [17]	✓	✓	×	✓	×
Brant-X [22]	✓	✓	×	✓	✓
FM-APP [39]	✓	×	×	✓	✓

"Cross scenarios": the ability of BFMs to operate effectively across diverse settings and conditions within a single paradigm;

"Cross tasks capability": BFMs can achieve robust performance across different paradigms.

Zhou, Xinliang, et al. "Brain Foundation Models: A Survey on Advancements in Neural Signal Processing and Brain Discovery." *arXiv preprint arXiv:2503.00580* (2025).

Rest of the talk

1. Fundamentals
   - ✓ Why Foundation Models for BCI?
   - Building Foundation Models (Pretraining)
   - Using BCI Foundation Models (Fine-tuning)

   Terminology for upcoming talks & discussions: *Autoencoders, latent representations, embeddings, SSL, contrastive learning, masked prediction, autoregression, foundation models, downstream tasks, frozen encoder, backbone weights, task head, zero-shot and few-shot learning, linear probing, fine-tuning, LoRa*

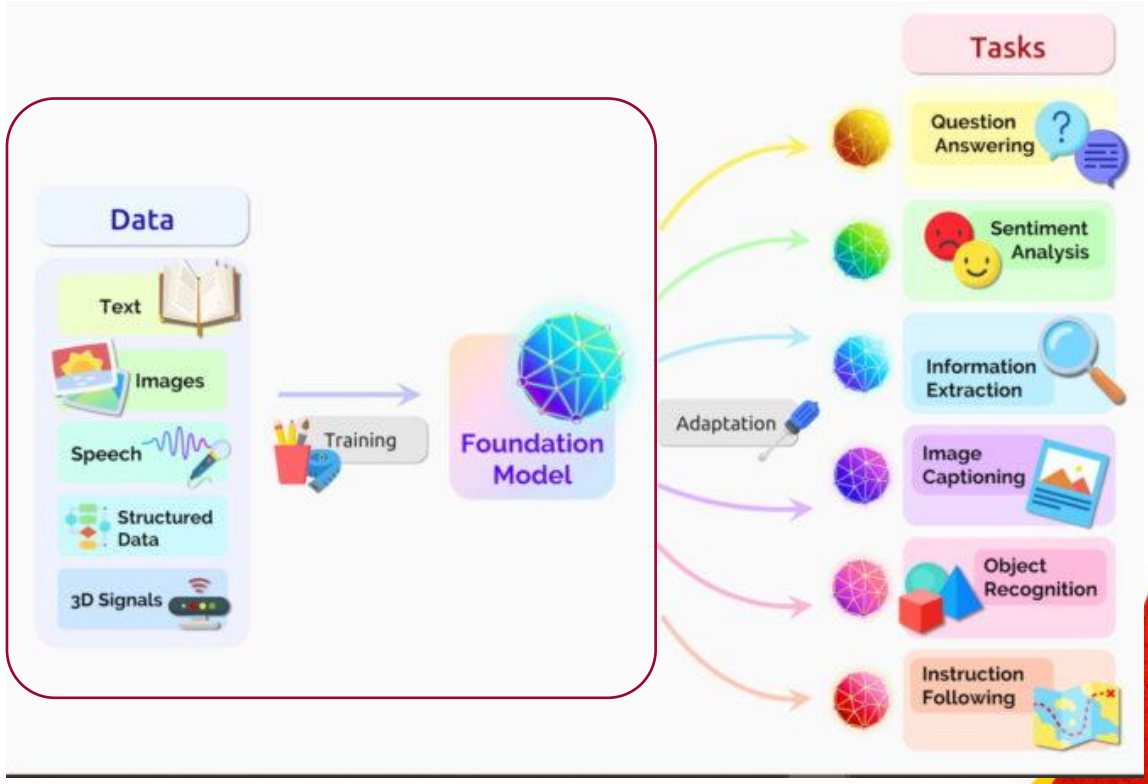
2. Opportunities

- Q&A (if needed!)

“Building” & “Using” BCI Foundation Models

How are Foundation Models trained?

- Typically, on large datasets using self-supervised learning (SSL)
- SSL does not rely on manually labeled data and uses the structure of the data itself to create “learning objectives”.



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Autoencoders – Preliminaries

- Learn to compress and reconstruct data
- Encoder maps input to a lower dimension (e.g. feature space)
- Decoder reconstructs original input

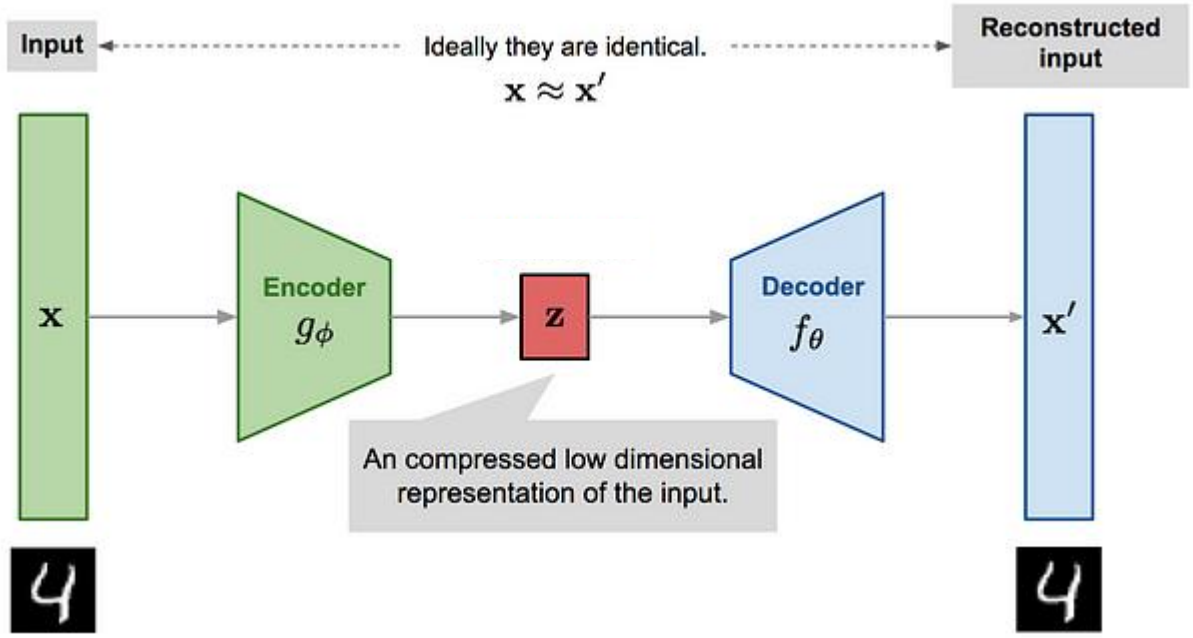
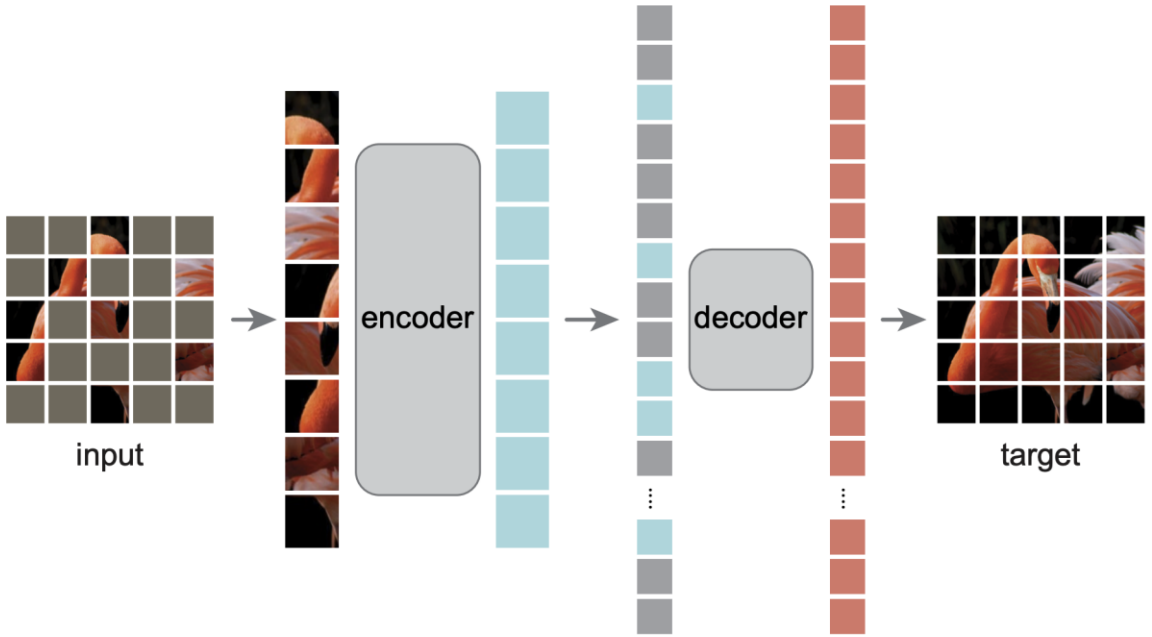


Illustration of the Autoencoder architecture. Source: Lilianweng's blog

Self-Supervised Learning – *Pretraining without labels*

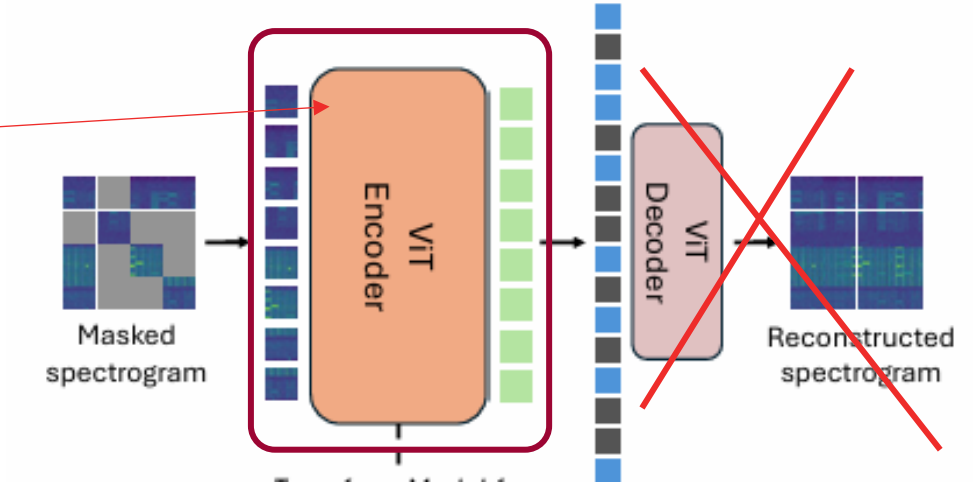
- Form of deep learning that does not require labeled data
- Learns from the data itself using a “pretext task” to generate supervision
  - **Predicting masked portions of input** is a common pretext task



Divide an image into patches and reconstruct the missing patches

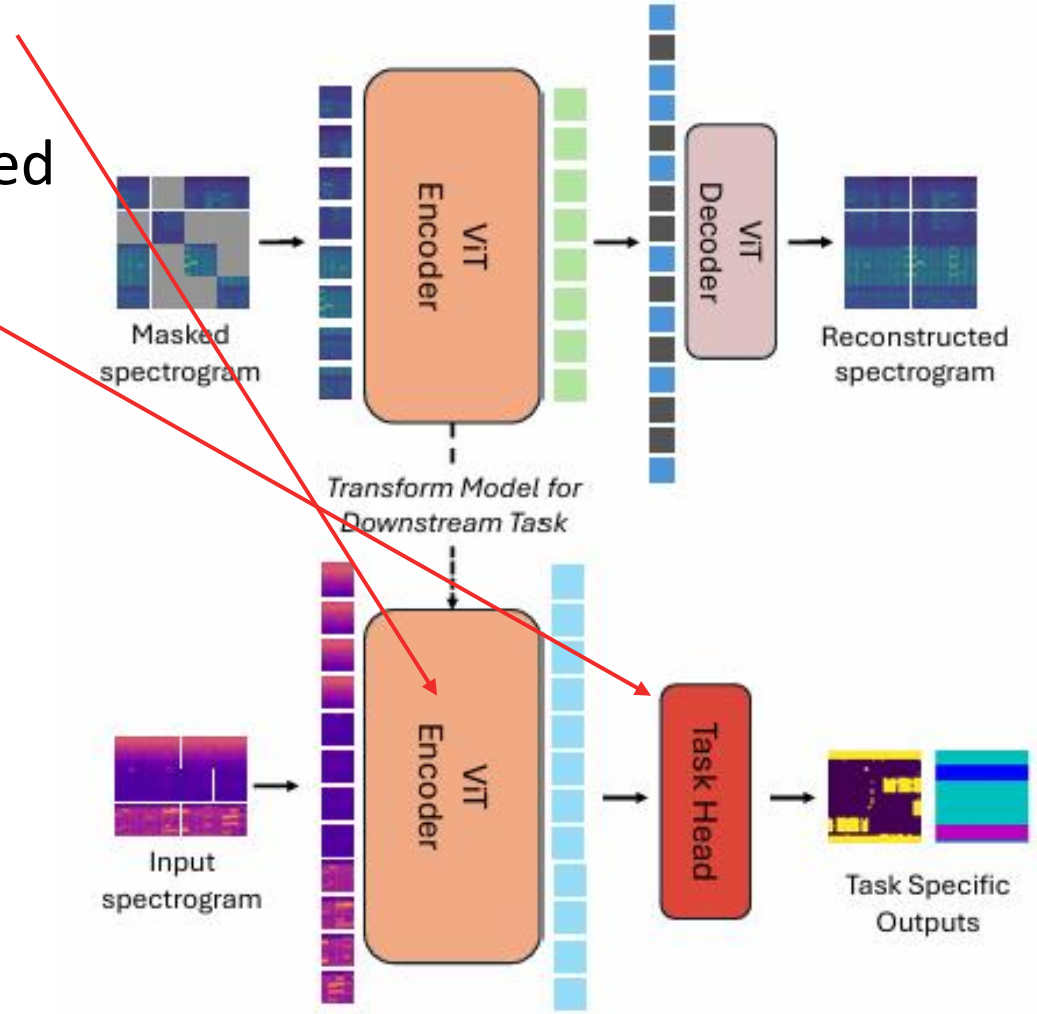
The encoder is the foundation model

- An example for a spectrogram foundation model
- After pretraining, the decoder is discarded
- **The FM is the encoder**



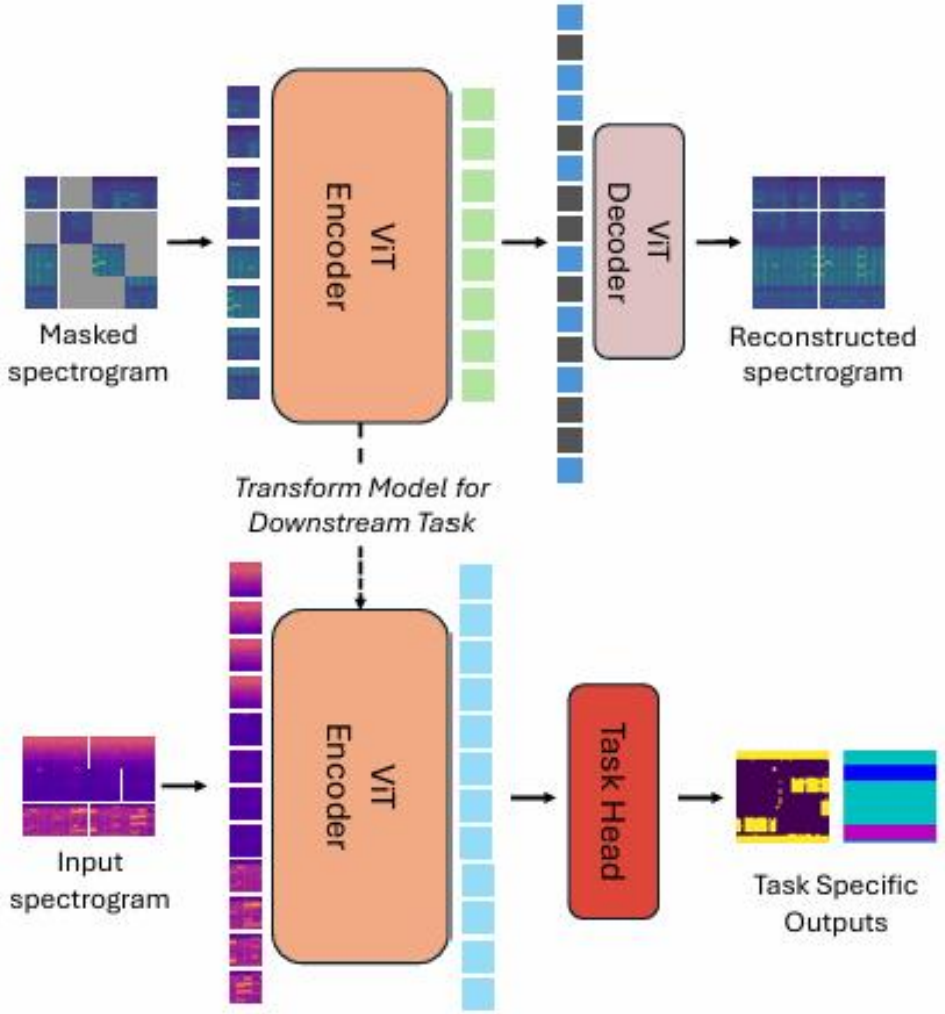
Learning a new task

- Re-use the learned encoder for features
- A simple classifier called the “task head” is added to the model
  - This can be a multi-layer perceptron (MLP) neural network

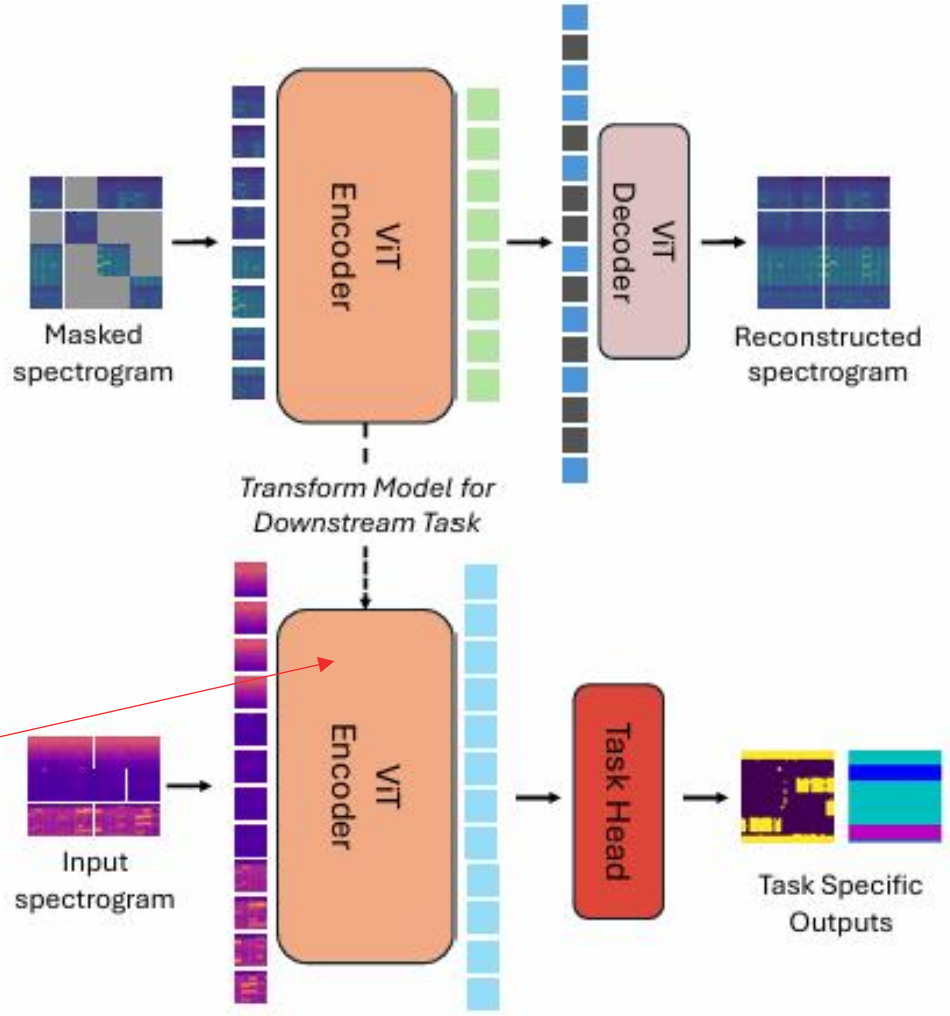


Learning a new task

- The “task head” weights are learned by processing labeled “task” data through the encoder and the task head/classifier
- Note that the encoder is not re-trained here
  - This is commonly termed as a “frozen encoder/FM weights”
- An example is teaching the model to segment spectrograms or classify objects



Can we fine-tune the encoder?

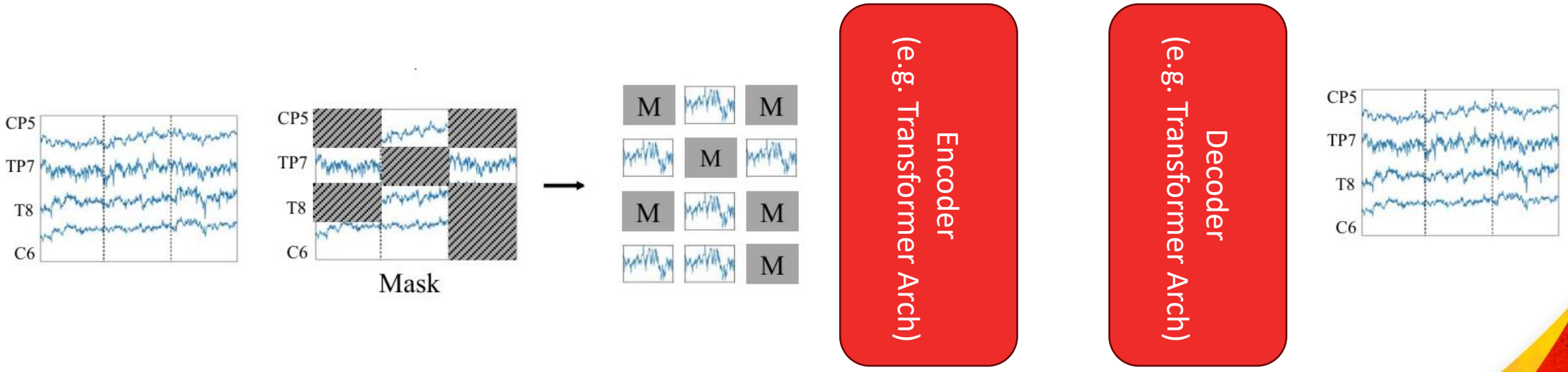


- Fine-tuning the encoder is also possible and involves updating some of the encoder weights
- There are very efficient ways to do this

When might we need this?

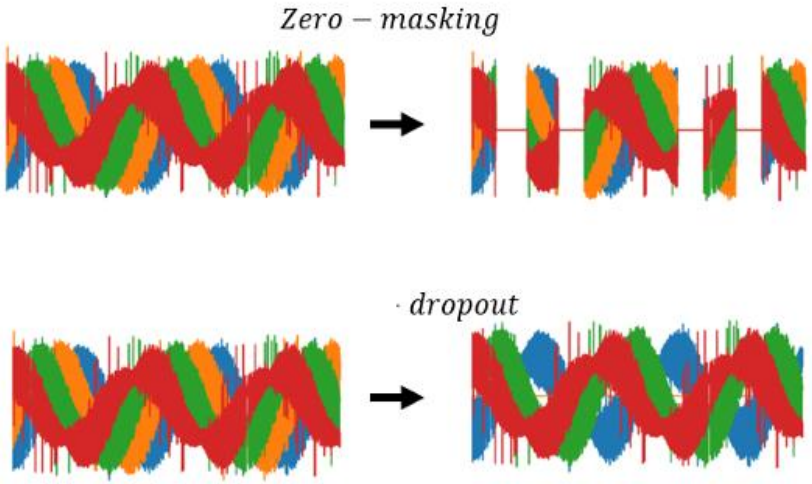
How can we apply this to EEG signals?

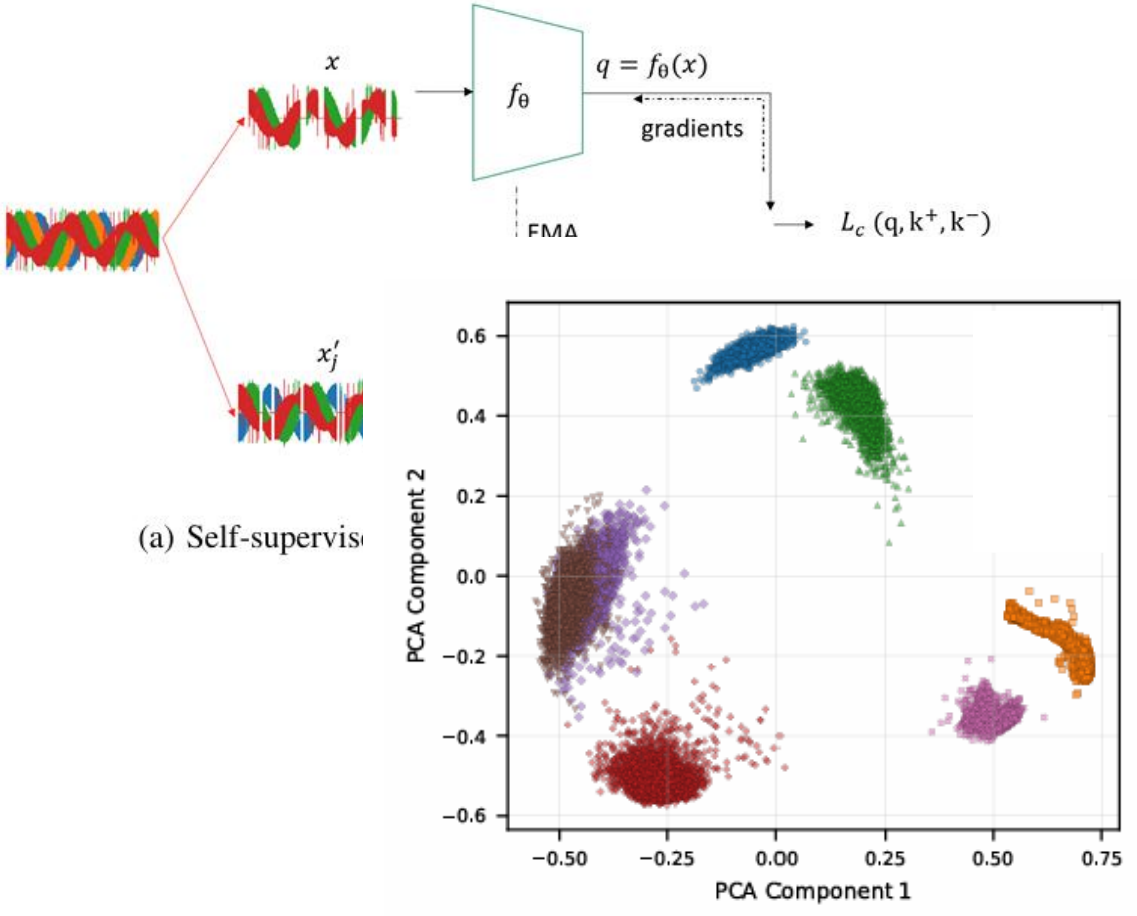
- Transform the channel-time EGG signals into “patches” of channels and temporal segments
- Apply a similar Encoder- Decoder structure to reconstruct the masked EEG signals
- Discard the decoder and use the encoder as the foundation model for new BCI tasks



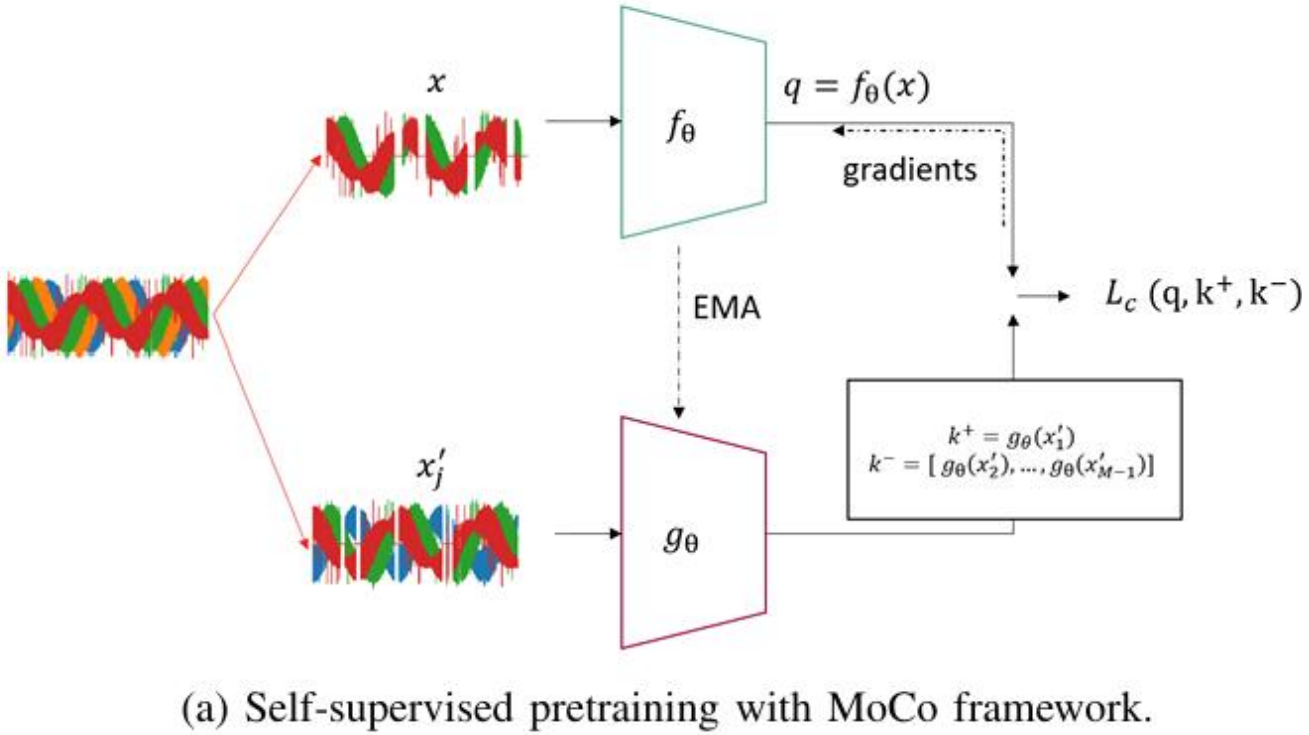
This is one approach but there are many other self-supervised learning approaches and variants!

Contrastive Learning – *Signal Augmentations*

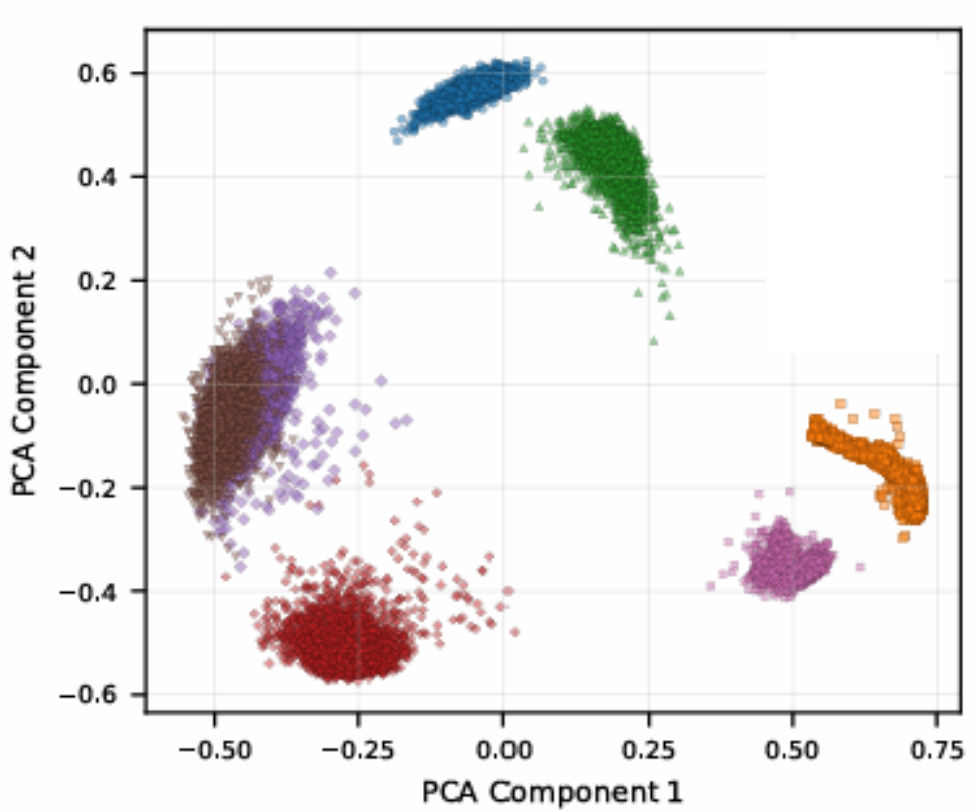




Contrastive Learning – *Clusters created*



(a) Self-supervised pretraining with MoCo framework.



Opportunities

Thank You!

Questions?

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